

## **THE NASA B-757 HIRF TEST SERIES - FLIGHT TEST RESULTS -**

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### **ABSTRACT**

In 1995, the NASA Langley Research Center conducted a series of aircraft tests aimed at characterizing the electromagnetic environment (EME) in and around a Boeing 757 airliner. Measurements were made of the electromagnetic energy coupled into the aircraft and the signals induced on select structures as the aircraft was flown past known RF transmitters. These measurements were conducted to provide data for the validation of computational techniques for the assessment of electromagnetic effects in commercial transport aircraft.

This paper reports on the results of flight tests using RF radiators in the HF, VHF, and UHF ranges and on efforts to use computational and analytical techniques to predict RF field levels inside the airliner at these frequencies.

### **INTRODUCTION**

Over the past two decades, digital technology has brought about significant advances in flight control, propulsion control, communications, and navigation functions of commercial aircraft. Advances in these areas are expected to continue in the future, with digital avionics being employed to perform increasingly complex functions; such as stability augmentation, gust load alleviation, and satellite-guided navigation. As the complexity and criticality of the functions performed by the on-board electronics increases, so does concern about the vulnerability of these systems to electromagnetic interference (EMI). Sources of EMI that are of particular concern are man-made radio frequency (RF) sources generated external to the aircraft, such as radar and radio transmitters. These potential sources of EMI are collectively known as HIRF or High Intensity Radiated Field sources. The National

Aeronautics and Space Administration (NASA) has become concerned about the threat that HIRF poses to the safe operation of civilian airliners and is funding an investigation, through the Aviation Safety Program, to find ways to quantify and reduce this threat.

A series of aircraft flight tests which supports this objective was conducted by the NASA Langley Research Center. These flight tests characterized the internal electromagnetic environment (EME) to which onboard equipment are subjected during flight. The test object for these flight tests was a commercially configured Boeing 757 owned by NASA. This aircraft was instrumented with an array of sensors positioned so as to study the electromagnetic coupling characteristics and shielding effectiveness of the aircraft's three main compartments; the flight deck, the avionics bay, and the passenger cabin. The aircraft performed a series of flights over fixed-frequency RF transmitters operating at specified output power levels and modulation schemes. These flights took place over a Voice of America (VOA) station located near Greenville, North Carolina and over sources located at the NASA Wallops Flight Facility on Wallops Island, Virginia.

The data from these flight tests were collected with the intent that they be used for the validation of computational, analytical and experimental techniques for the prediction of the EME inside aircraft. Validated EME prediction techniques could, for example, provide avionics designers knowledge about the effects of HIRF threats on internal electronic systems early in the aircraft design process. Such knowledge would improve the design process, resulting in more robust and cost-effective designs. Validated EME prediction techniques could also improve the validity of laboratory testing of avionics systems, since accurate knowledge of the EME inside an aircraft is required before it can be reproduced in the laboratory. The data collected during these flights, observations about these data, and efforts to

develop computational EME prediction techniques and verify them against these data are the subject of this paper.

## FLIGHT TESTS

The EME flight experiments were conducted over several days in February 1995. The NASA 757 research aircraft flew a total of 56 data runs against four RF sources. These runs consisted of several different flight profiles relative to the RF source. The flight commander, with the aid of the 757's preprogrammed flight management system, piloted the aircraft according to a number of parameters established for each profile. Flight profiles were planned to insure that electromagnetic energy impinged upon the aircraft fuselage at various angles of incidence. Inbound and outbound flight paths were executed to illuminate the nose and tail of the aircraft and crossbound flight paths were executed to illuminate the left and right sides.

For each inbound path, outbound path, and crossbound path, the aircraft was configured in one of three configurations. These configurations were designated clean, flaps, and flaps & gears. The clean configuration was flown with the aircraft control surfaces trimmed to neutral and the landing gear up with the bay doors closed. The flaps configuration was flown with the aircraft flaps extended to 15 degrees. The flaps & gears configuration was flown with the landing gear down, the gear bay doors open, and the flaps extended to 15 degrees. These three configurations were planned to help define EME coupling apertures and to determine if changes in the aircraft configuration significantly affected shielding effectiveness.

## RF SOURCES

Flight tests were conducted at four of five frequencies recommended by a committee of government and industry representatives formed at the FBL/PBW workshop held at NASA Langley Research Center in March 1992. Only three of these four frequencies are discussed in this paper.

The RF source located at the VOA site near Greenville, NC was a rhombic antenna (known as BR-17) located at the "Site B" complex. This antenna is a diamond-

shaped wire antenna, where each side of the diamond is a 300 ft long catenary wire suspended from steel towers that are 80 ft high. This antenna was driven by a 500 kW continuous wave transmitter operating at a frequency of 25.85 MHz. This antenna has a gain of 23 dBi at a take-off angle of 7 degrees at this frequency. Radiation from this antenna was fixed in the horizontal polarization with a beamwidth of 14° in both the E and H-planes.

RF sources located at the NASA Wallops Flight Facility included sources operating at 173 and 430 MHz. The 173 MHz source was a portable log-periodic antenna driven by a 500 W continuous wave transmitter, both of which were provided by the US Naval Surface Warfare Center - Dahlgren Division. This antenna has a gain of 7.5 dBi, an E-plane beamwidth of 60° and H-plane beamwidth of 105°. Data were collected with this antenna positioned in both the vertical and horizontal polarizations. In both cases, the antenna was fixed in position and did not track the aircraft. When fixed in the horizontal polarization, the take-off angle was set at 50°; in the vertical polarization, the take-off angle was set at 30°.

The 430 MHz source was a ranging and tracking radar system that tracked the aircraft while data were being collected. The source antenna for this system is a 60 ft parabolic reflector with 36 dBi of antenna gain. The associated transmitter was operated at an output power level of 58 kW using a 2 microsecond pulse width modulation at a pulse repetition rate of 1280 pulses per second. Radiation from this antenna was fixed in the vertical polarization over a beamwidth of 2.9° in both the E and H planes.

## FLIGHT SENSORS

The NASA 757 was instrumented with an array of electric field sensors, current sensors, and measurement hardware. Sensing devices were integrated into a real-time data acquisition system. This system consisted of two equipment racks containing all of the instrument controllers and receiving equipment, and was located in the first class section of the 757's passenger cabin. A GPS receiver and the aircraft's own flight instruments were used by the measurement system to acquire aircraft latitude, longitude, altitude, yaw angle, pitch angle, and

roll angle. Data from the aircraft's flight instruments were recorded directly from the aircraft's internal data bus.

Six RF sensors, illustrated in Figure 1, were used as probes to directly measure the electromagnetic environment inside the aircraft. These sensors consisted of three Prodyn Technologies AD-60 D-dot electric field sensors, a long wire antenna, and two Prodyn I-320 current sensors.

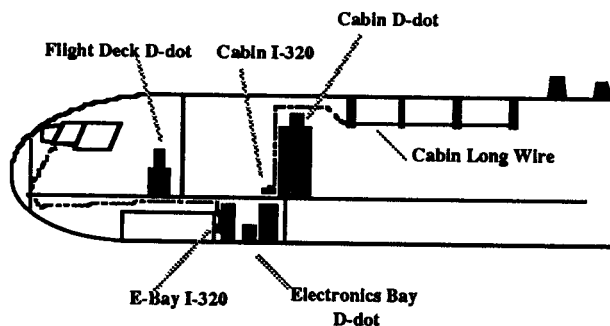


Figure 1. Sensor locations

Prodyn AD-60 D-dot sensors are hemispherical electric field sensors designed to measure time rate-of-change of the electric field over a wide frequency spectrum. One vertically oriented D-dot sensor was positioned in each of the aircraft's three main compartments; the flight deck, the electronics bay, and the passenger cabin. The Flight Deck D-dot was mounted on a metal box located aft of the first officer's seat, the Electronics Bay D-dot was located in the main electronics equipment bay aft of the nose wheel well, and the Cabin D-dot was located on top of one of the equipment racks housing the data acquisition system in the first class section of the passenger cabin. D-dot sensors are specified by the manufacturer to operate at frequencies greater than 400 MHz, however detailed calibration measurements performed by the National Institute of Standards and Technology (NIST) for NASA permitted the use of these sensors at all of the flight test frequencies.

The long wire antenna was a 20 foot long wire that ran in the direction of the longitudinal axis of the aircraft and was suspended with dielectric standoffs one foot below the ceiling of the passenger cabin, terminated in a 50 ohm cable, across which the voltage was

measured. This antenna was extremely broadband and was responsive to signals across the test spectrum.

Prodyn I-320 current probes are clamp-on devices that were used to sense currents induced onto the shielding of wire bundles in the aircraft. Two I-320 current probes were used for this experiment. One was located in the main electronics bay and was coupled to a cable that ran from the electronics bay along the interior left side of the aircraft fuselage to the flight deck windscreen heat mesh embedded in the captain's window. This sensor was used to sense currents that were theorized to be induced onto cable bundles from external electromagnetic energy impinging on the nose of the aircraft and entering the window apertures of the aircraft's flight deck. The other current probe was located in the passenger cabin and was used to sense currents on the shielded outer conductor of the semi-rigid coaxial cable feeding the long wire antenna. Calibration information for these sensors was provided by the US Air Force Phillips Labs.

## POST-FLIGHT DATA REDUCTION

Subsequent to the conclusion of the flight tests, a number of steps were taken in order to make the flight data suitable for comparison with computational predictions. The first among these was to determine the direction of arrival of the incident radiation in a coordinate system fixed to the airframe. Aircraft pitch, yaw, and roll angles were recorded along with aircraft altitude and distance from the RF source (determined by the aircraft flight computer from GPS receiver information) for each point in every data run for which internal EME data was recorded. This information was used to determine the (theta, phi) coordinates of a vector connecting the origin of a spherical coordinate system fixed to the aircraft to the RF source on the ground for every point in the data run.

Another issue was the determination of the EME outside of the aircraft as it flew past the RF sources. Computational simulation of the flight experiment requires that the field strength of the free-field EME (the field that would be measured if it were not perturbed by the aircraft) be known. Determination of this field strength from measurements made by sensors on the exterior of the aircraft proved infeasible, so an effort

was undertaken to determine the field strength using computational simulations of the RF sources.

The 25.9 MHz VOA rhombic antenna and the 173 MHz log-periodic antenna were both modeled using the Numerical Electromagnetics Code (NEC), a method-of-moments based software package developed by the Lawrence Livermore National Laboratory. In both cases, NEC models of these antennas predicted gain and beamwidth parameters that were found to have excellent agreement with antenna specifications. Once the flight data had been processed to determine aircraft position relative to the antenna at each point in every 25.9 and 173 MHz data run, the NEC models were used to calculate the free-field EME at each of these points. Attempts were made to use the NEC models to predict field levels measured by on-the-ground site surveys of these antennas. For the most part, these attempts were met with disappointing results. The inability to demonstrate a capability to predict measured field levels adds considerable uncertainty to the calculated free-field EME levels, primarily by raising the possibility that the calculated free-field EME levels are corrupted by a systematic error introduced by the estimation of the power level at the antenna feed points.

Free-field EME levels at measurement points in the 430 MHz data runs were calculated using the NECREF reflector antenna program developed at the Ohio State University. This program employs aperture integration and the geometrical theory of diffraction. The 430 MHz antenna was slaved by a radar tracking system such that the aircraft was in the center of the antenna beam during each data run. Therefore, it was necessary only to know the distance from then antenna to the aircraft in order to use this program. Like the free-field EME calculations made at 25.9 and 173 MHz, the EME calculations at 430 MHz have not been confirmed measurement.

## DATA ANALYSIS

Three different types of flight profiles were flown over the 25.9 and 173 MHz sources; crossbound, inbound, and outbound. Crossbound flights had ground tracks that were circles of constant radius with the source antenna at the center. These flights illuminated the right or left side of the aircraft (for clockwise or

counter-clockwise directions, respectively). Inbound and outbound flights were flights directed towards and away from the antenna and through the center of the main beam. These flights illuminated the nose and tail of the aircraft, respectively.

EME data collected at 25.9 MHz shows that very little energy was measured by sensors in the flight deck or the electronics bay at this frequency. This result is not surprising since 25.9 MHz is well below the cutoff frequency (the minimum frequency at which a mode can be sustained in an electromagnetic cavity) for these compartments. Sensors in the passenger cabin showed a surprising amount of sensitivity to the configuration of the flaps and landing gear. The character of this sensitivity can be seen by comparing EME data collected during the nose-illuminating inbound flights, shown in Figure 2, with the data collected during the tail-illuminating outbound flights shown in Figure 3. Tail-illuminating flight data show that EME levels inside the cabin are approximately three times higher when the flaps are deployed 15° ("flaps") than when the flaps are set to the neutral position ("clean"). The data presented in Figures 2 and 3 is that collected from the cabin D-dot sensor, but this phenomenon (EME sensitivity to aircraft configuration for rearward illumination) is also seen in the data collected by the cabin long-wire sensor.

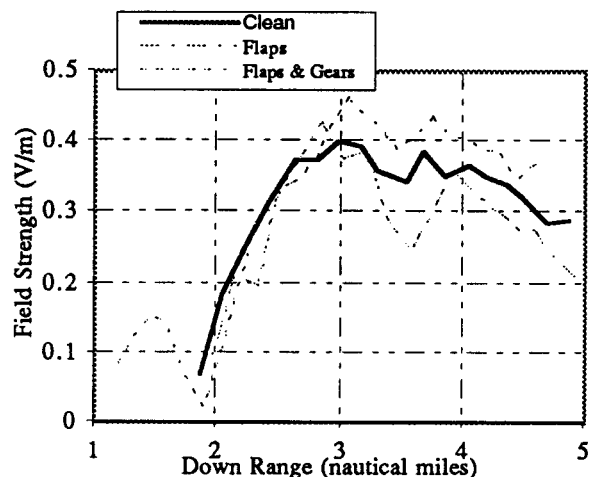


Figure 2. Cabin D-dot sensor data for inbound flights at 25.9 MHz

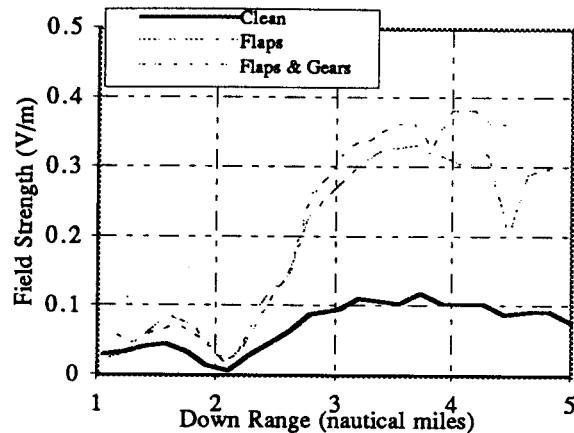


Figure 3. Cabin D-dot sensor data for outbound flights at 25.9 MHz

This result is possibly explained by the fact that deploying the flaps opens apertures into the rear wheel-bays of the aircraft. This explanation makes it seem likely that there are significant EME coupling paths connecting the wheel bays to the passenger cabin. Note that it was not possible for the aircraft to fly exactly the same path for the three data runs presented in each of these figures. Variations in altitude (up to  $\pm 150$  meters), ground track (up to  $\pm 150$  meters), pitch angle, roll angle, and yaw angle were observed between these data runs.

Unlike the data collected at 25.9 MHz, energy was measured by sensors in all three compartments at 173 MHz. Cabin D-dot sensor and long-wire sensor data show the same sensitivity to aircraft configuration for rearward illumination that was observed at 25 MHz. Another interesting observation about the data collected at 173 MHz relates to the response of the Electronics Bay I-320 current probe that was coupled to a cable that ran from the electronics bay to the heat mesh embedded in the captain's window. During nose-illuminating inbound flights, the response of this sensor was found to more closely correlate with the response of the Flight Deck D-dot sensor than with the response of the Electronics Bay D-dot sensor. This behavior seems to indicate that cable bundles do in fact couple external EME impinging on the nose of the aircraft into the Electronics Bay, as had been theorized prior to these flight tests.

Since the source antenna at 430 MHz was slaved to track the aircraft, it was necessary only to fly "lazy L" type ground tracks in order to illuminate the nose, tail, and sides of the aircraft. Data from these flights are still being studied and conclusions have not been drawn from them.

## COMPUTATIONAL SIMULATION

The technique chosen for computational simulation of the EME flight experiments is the Finite Difference Time Domain (FDTD) method, which is perhaps the most popular method for solving complex electromagnetic problems. The popularity of this method may be attributed to FDTD's ability to handle arbitrary and complex geometries which include materials of arbitrary composition. In the most frequently used implementation of this method, physical objects are approximated using cubical cells which are between one-tenth and one-twentieth of a wavelength on edge. Each cell is assigned material parameters which describe the electromagnetic properties of the material of interest (metal, free-space, dielectric, etc.). Discrete approximations of Maxwell's equations are then used to compute the interaction of electromagnetic fields with the material cells as a function of time.

Solution of the EME inside a Boeing 757 presents a number of challenges to the use of the FDTD method. Chief among these are the complexity and the size of the physical object being modeled. The FDTD method requires that six vector electromagnetic field components be stored in computer memory for every cell. Since 10 to 20 cells per wavelength are needed to create an approximation of a physical object with this method, the amount of computer memory available will limit the electrical size (in wavelengths) of the physical object that can be approximated. Solution of the electromagnetic interaction with physical objects as large as 3000 cubic wavelengths is considered the current state-of-the-art in the use of the FDTD method. At 173 MHz, the electrical size of a Boeing 757 is 4,600 cubic wavelengths. At 430 MHz, the electrical size jumps to nearly 70,000 cubic wavelengths. Obviously, it will not be possible to model more than a portion of the aircraft at higher frequencies; however

use of only a portion of a physical object presents yet another challenge to the use of the FDTD method.

Creation of a cubic-cell approximation of the NASA 757 began with the development of a CAD (Computer Aided Design) description of the aircraft. The CAD software used for this was MGED, part of the BRL-CAD software package which is available from the US Army Ballistic Research Laboratory. Initial development of the 757 CAD model was performed by the Lawrence Livermore National Laboratory (LLNL), using CAD descriptions and drawings provided by the Boeing Company. The information provided by Boeing was developed as part of the manufacturing process and lacked sufficient detail to fully describe the electromagnetic properties of the aircraft. Interior detail, such as seats, lavatory and galley bulkheads, cockpit panels, luggage bins, and the equipment used in the experiment, as well as exterior detail, such as wing fairings, were added by engineers at LLNL and NASA. A study was undertaken by NASA to determine the electromagnetic properties of the non-metallic materials used in and on the 757 and this information was also added to the CAD description.

From this CAD description, a cubic-cell approximation was obtained using ANASTASIA, which is part of the TSAR software package available from LLNL. 15 cells per wavelength and seven different types of materials were used to create a cubic-cell approximation of the full aircraft for 173 MHz simulations. This model is comprised of 17.4 million cells and requires just over 1 Gigabyte of computer memory for it to be solved.

Solution of the EME inside this cubic-cell approximation has been demonstrated using FDTD software which was developed collaboratively by NASA and Arizona State University to be efficient in solving very large problem sizes. This software is most efficient when used on vectorizing multi-processor platforms. As of this writing, this software has been exercised on a 4-processor Silicon Graphics Onyx (which is rated to be capable of over 1 Gflops), and a 16-processor Cray C-90 supercomputer (rated at 8 Gflops). Efforts are currently underway to calculate solutions for a number of points in data runs at 25.9 and 173 MHz. Much work remains to be done,

including the development of solution acceleration techniques and the development of techniques to enable the use of FDTD at higher frequencies.

## CONCLUSION

A unique flight experiment in which a large commercial transport aircraft's interaction with a defined electromagnetic environment has been described. Supporting ground facilities and related hardware were illustrated to present the various types of RF sources used in this experiment. A data reduction process was developed for the purpose of reducing the flight data to a form suitable for empirical analysis and comparison with EME modeling predictions. Examples of these data were introduced.

Conclusions drawn from the data set include the observation that coupling along cable bundles cannot be ignored by computer models at 173 MHz. It was also observed that the EME inside the aircraft is strongly dependent upon the position of the wing flaps and landing gear at 25.9 and 173 MHz for certain directions of the arriving illumination. The development of a CAD description of the NASA 757, and its subsequent use in the a computer model of the flight experiment was also described.

## ACKNOWLEDGMENTS

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